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Lifetime of Particles Containing b Quarks*

E. Fernandez, W. T. Ford, A. L. Read, Jr., J. G. Smith
Department of Physics
University of Colorado, Boulder, Colorado 80309

R. De Sangro, A. Marini, I. Peruzzi, M. Piccolo, F. Ronga
Laboratori Nazionali Frascati dell' I.N.F.N., Italy

H. T. Blume, H. B. Wald, Roy Weinstein
Department of Physics
University of Houston, Houston, Texas 77004

H. R. Band, M. W. Gettner, G. P. Goderre,
B. Gottschalk,[a] R. B. Hurst, O. A. Meyer,
J. H. Moromisato, W. D. Shambroom, E. von Goeler
Department of Physics
Northeastern University, Boston, Massachussets 02115

W. W. Ash, G. B. Chadwick, S. H. Clearwater,
R. W. Coombes, H. S. Kaye, K. H. Lau, R. E. Leedy,
H. L. Lynch, R. L. Messner, S. J. Michalowski,[b] K. Rich,
D. M. Ritson, L. J. Rosenberg, D. E. Wiser, R. W. Zdarko
Department of Physics and Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

D. E. Groom, Hoyun Lee, E. C. Loh
Department of Physics
University of Utah, Salt Lake City, Utah 84112

M. C. Delfino, B. K. Heltsley, J. R. Johnson, T. L. Lavine,
T. Maruyama, R. Prepost
Department of Physics
University of Wisconsin, Madison, Wisconsin 53706

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(a). Present address: Cyclotron Laboratory, Harvard University, Cambridge, MA 02138

(b). Present address: Mechanical Engineering Department, Stanford University, Stanford, CA 94305

ABSTRACT

From a sample of hadronic events, produced in e^+e^- collisions, we have isolated semi-leptonic decays of heavy particles and used these to obtain a measurement for the bottom-quark lifetime of $(1.8 \pm 0.6 \pm 0.4) \times 10^{-12}$ sec.

According to the standard six quark model, the decay of the lowest-lying bottom-flavored hadrons is forbidden in the absence of mixing of b quarks with either s or d quarks (or both). The values of mixing angles, as defined, for example, by Kobayashi and Maskawa[1] or by Maïani[2], can be constrained by a measurement of the b lifetime. In the present experiment semi-leptonic decays have been used to isolate bottom-flavored particles, produced in e^+e^- annihilations to hadrons, and to determine their lifetime.

The MAC detector[3], operating at the PEP storage ring, includes a cylindrical drift chamber for tracking charged particles, consisting of ten layers of drift wires in a solenoidal magnetic field of 5.7 kG. The radii of the inner- and outermost layers are 12 cm and 45 cm, respectively. The range of polar angles subtended by all ten layers is 23° to 157°. Each cell contains a double sense-wire pair connected to differential electronics so that drift distance is determined without right-left ambiguity. The wires in four of the layers are axial; these are interspersed with six stereo layers at plus and minus three degrees to determine axial positions. The point measurement accuracy is about 200 μm.

The drift chamber is surrounded, in a hexagonal geometry, by electromagnetic and hadron calorimeters. Layers of lead interspersed with proportional wire chambers constitute the electromagnetic shower chamber, amounting to 16 radiation lengths of material. In the hadron calorimeter, layers of steel alternate with proportional wire chambers, such that normally incident particles traverse 92 cm of steel. The hadron calorimeter and the shower chamber are each segmented into 192 azimuthal sectors and three radial layers from which independent readouts are obtained. Charge division is used to determine the axial position of showers in both detectors. Two endcap calorimeters, alternating steel and proportional chambers, cover angles greater than 10 degrees from the beam. The solid angle subtended by calorimeters is therefore about 98% of 4π. The calorimeter steel in both the central and endcap regions is magnetized to about 17 kgauss by toroid coils.

The entire calorimetric detector is surrounded by drift chambers whose purpose is muon tracking. These chambers determine the radial and axial components of the location and direction of particles penetrating the hadron calorimeters. Five of the sextants have four layers of cylindrical drift tubes, each with 88 cells per sextant, while the remaining sextant has three layers of drift planes.

The parent sample for this analysis consists of approximately 50000 multihadron events, selected according to the following criteria, based either on tracking information or energy flow vectors constructed from the calorimeters: an event must have (1) more than 4 charged prongs, (2) total visible energy in all calorimeters greater than the beam energy, (3) a scalar sum of the component of the energy vectors perpendicular to the beam greater than 9 GeV, and (4) a vector sum of the energy vectors with magnitude less than 55% of the visible energy. The muon (electron) sample corresponds to an integrated luminosity of 108 (92) pb^{-1} at a center-of-mass energy of 29 GeV.

Within these events, isolated tracks reconstructed in the drift chambers surrounding the calorimeter constitute muon candidates. A momentum measurement was made for each of these tracks by extrapolating it back through the toroidal magnetic field of the calorimeter to the primary event vertex, taking into account the ionization loss of the particle in the calorimeter. The momentum resolution is about 30%, due mostly to multiple scattering. It was further required that the track be matched in polar angle and momentum to a track reconstructed in the central drift chamber, and to a segment reconstructed from the energy deposited in the central or endcap calorimeter, with pulse heights corresponding to those of a single minimum-ionizing track. Finally, the momentum assigned to the muon candidate was the weighted average of toroid spectrometer and central drift chamber measurements.

An electron candidate is defined as a track in the central drift chamber associated with a shower in the electromagnetic shower chamber and with no significant energy deposition in the hadron calorimeter. Only tracks with momentum greater than 1.8 Gev/c and in the fiducial region $|\cos\theta| < 0.7$ are considered. The energy deposited in the calorimeters is measured in a cone around the direction of the track at the exit of the drift chamber and is required to follow a pattern typical of the development of an electromagnetic shower in our detector, as determined from non-radiative and radiative Bhabha events. The contamination in the sample, apart from c quark semileptonic decays, comes from ee pairs (photons converting in the vacuum pipe and Dalitz pairs), τ and ψ decays and hadron misidentification. About 50% of the electron pairs can be easily identified; the remaining contamination has been calculated not to exceed 25%.

To estimate the background and to study heavy flavor decay, we have constructed a Monte Carlo model to simulate the production and decay of hadrons[4] and to trace in detail their interactions and the response of the detector[5]. This program provided the spectra for both signal and backgrounds used in the analysis described below.

In a previous publication[6] we presented a measurement of the fragmentation function of b quarks. As described in detail there, discrimination between heavy and light quarks that decay to leptons is achieved via the total momentum of the lepton and by its component perpendicular to the thrust axis of the event ($p_\perp$): a heavy produced particle follows closely the direction of the primary quark which in turn is well approximated by the thrust axis. On decay, the heavy parent imparts a large transverse momentum to the daughter lepton. The specific cuts applied in the present analysis were total momentum greater than 2 GeV/c and $p_\perp$ greater than 1.5 GeV/c.

The lifetime of the particles which decay to produce the observed leptons is inferred from the distribution in impact parameter of the lepton tracks with respect to the interaction point. In Fig. 1 are defined the flight path, ℓ, of the parent hadron (e.g., B meson), the directions of travel of the parent and lepton (e.g., muon), the decay angle ψ and impact parameter δ, all as projected onto a plane perpendicular to the beam axis. The quantity δ is taken to be positive (negative) in the reconstructed events (where the B direction is unknown) if a forward (backward) laboratory decay angle would be inferred for the lepton, assuming the parent travelled along the thrust axis toward its intersection with the muon trajectory. The effect of approximating the B direction by the thrust axis is to cause a true positive δ to appear negative, when the angle of the muon trajectory falls between those of the B flight path and the thrust axis, diluting the observed effect. Detailed calculations show that the resulting loss of sensitivity from this effect is negligible for B's and about a factor of two for charm. On the other hand, for π and K decay and converted gamma ray backgrounds there is nearly complete cancellation.

The average value of δ computed from the observed distribution is proportional to the lifetime:

$$\langle\delta\rangle = \langle\beta\gamma \sin\psi \sin\theta\rangle c\tau \equiv \alpha c\tau, \qquad (1)$$

where θ is the polar angle of the track. The proportionality constant, α, has been computed using the Monte Carlo program, and is found to be very insensitive to the fragmentation function. Typically, the decay angle ψ shrinks as a function of parent momentum at about the same rate as the relativistic time dilation factor grows. The detailed calculation shows that α decreases by 11% as the B momentum is changed from 0.8 to 0.5 times the beam momentum.

The precision of the measurement of δ is determined by the precision of the extrapolation of the lepton track reconstructed in the central drift chamber, and by the effective size of the beam interaction volume, including the effect of any uncorrected shifts with time of the beam position. The beam position for each run was determined by a simultaneous fit to all of the Bhabha events in that run. A plot of the results as a function of time was then used to establish beam position values for each block of runs between significant changes. From these data we find the effective rms beam size to be about 0.4 mm (horizontal) by 0.1 mm (vertical). The uncertainty of the track extrapolation was obtained from the error matrix for each track fit. Fig. 2 shows the distribution in the uncertainty of δ; events having uncertainty less than 1 mm are entered into the histograms of δ, Fig. 3, weighted by the corresponding reciprocal squared errors. The mean values $\langle\delta\rangle$ from these distributions are listed in Table 1.

In terms of the separate components of the data sample, the average value of δ is given by

$$\langle\delta\rangle = f_b \alpha c \tau_b + f_c \delta_c + f_{bg} \delta_{bg}. \qquad (2)$$

Here the subscripts b,c and bg refer to b- and c-flavored particles and to background, respectively, f_i is the fraction of the sample corresponding to component i, and the factor α is defined in equation (1). Here f_c includes cascades b→c→lepton. The values of these parameters are given with their uncertainties in Table 1. They were determined from the Lund model plus MAC detector Monte Carlo program discussed above. The heavy-quark fragmentation therein was adapted to agree with the measured fragmentation functions[6-8]. The b leptonic branching fraction used was 15%, as measured previously[6] with a sample partially overlapping the present one. The charm leptonic branching fraction was taken to be[8,9] 8%, and the lifetimes of charm particles used in the calculation are[10] (D^0) 4.0×10^{-13}; ($D^{\pm}$) 9.3×10^{-13}; ($F^{\pm}$) 2.9×10^{-13}; (Λ_c) 2.2×10^{-13}.

As a check for bias in the distribution of δ a control sample was made from the parent multihadron sample by taking all charged particle tracks assigned to the primary vertex which pass the same momentum and $p_\perp$ cuts required for the leptons. Momentum and $p_\perp$ distributions of the surviving events are quite similar to those of the leptons. The resulting weighted $\langle\delta\rangle$ for 2963 tracks is 17±20 μm, to be compared with about 19 μm expected from charm and bottom particles in the control sample. In contrast, both signal samples give about 160 μm. Assigning a systematic uncertainty of 30 μm for $\langle\delta\rangle$ and combining with the other systematic errors quoted in Table 1 (which in turn reflect the uncertainties in the various inputs to the Monte Carlo), we find finally

$$\tau_b = (1.8 \pm 0.6 \pm 0.4) \times 10^{-12} \text{ sec.}$$

This may be compared with earlier limits[11], of which the most stringent is $\tau_b < 1.4\times10^{-12}$ sec, reported by the JADE collaboration.

In terms of the mixing angles of Maiani[2], the standard model prediction for τ_b is given by[12]

$$\frac{1}{\tau_b} = 1.08\times10^{14}\left[\frac{m_b}{5\text{ GeV}}\right]^5 (2.75\sin^2\gamma + 7.69\sin^2\beta - 5.75\sin^2\beta\sin^2\gamma) + O(\beta^4,\gamma^4)\text{ sec}^{-1}. \quad (3)$$

In combination with the measured limit on the non-charm branching fraction of b particles[13],

$$B\left[\frac{b\to u}{b\to c}\right] = \left[\frac{\tan\beta}{\sin\gamma}\right]^2 < 0.055, \qquad (4)$$

our result for τ_b implies $|\sin\gamma| = 0.043^{+0.012}_{-0.009}$.

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Table 1

Summary of parameters used to compute τ_b.

	μ sample	e sample
No. of events	155	113
f_b	0.72±0.08	0.63±0.07
f_c	0.14±0.04	0.12±0.05
f_{bg}	0.14±0.07	0.25±0.08
δ_c (μm)	24 ± 11	19 ± 11
δ_{bg} (μm)	<50	<80
α	0.43±0.03	0.46±0.03
$\langle\delta\rangle$ (μm)	158 ± 81	174 ± 75
τ_b (10^{-12} sec)	1.62±0.87	1.97±0.86

Figure Captions

Fig. 1. Direction vectors and production and decay points relevant to heavy hadron leptonic decay.

Fig. 2. Distribution of measurement uncertainties of the decay impact parameter, δ.

Fig. 3. Distributions of δ for (a) muons and (b) electrons.

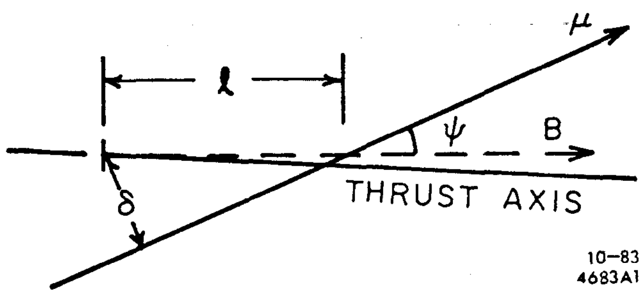

Fig. 1

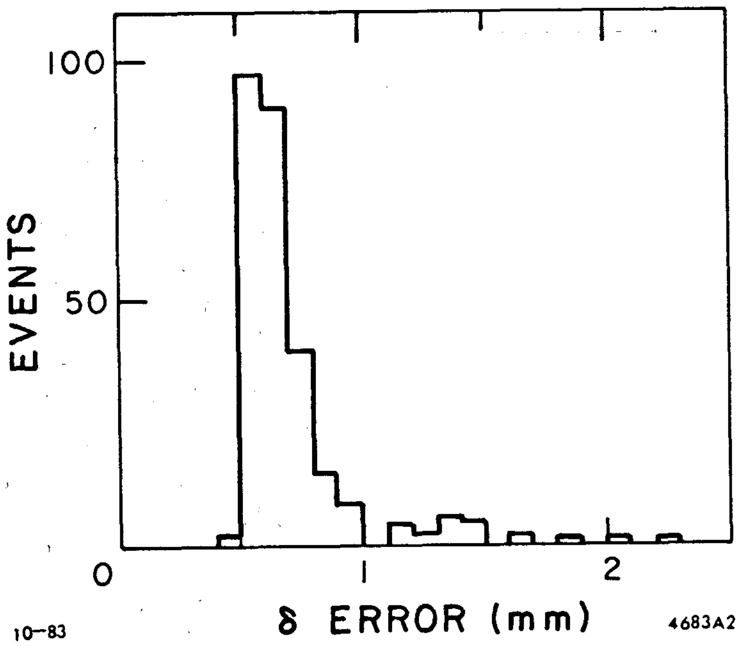

Fig. 2

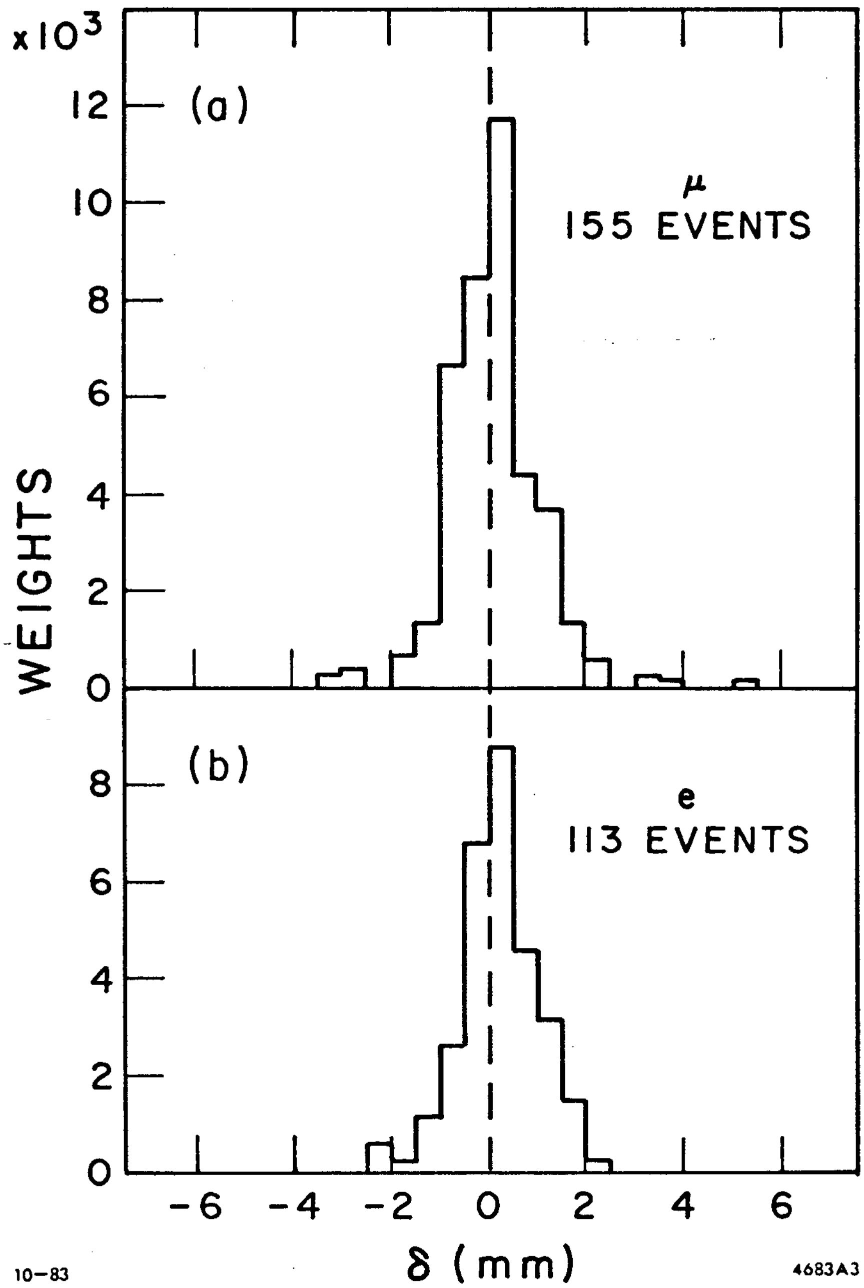

Fig. 3